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Responsible or reckless? A critical review of the environmental and climate assessments of mineral supply chains

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This paper critically reviews and identifies gaps in the methodologies used to analyze the environmental impacts of mineral and metal global supply chains. Of specific focus are assessments of the extraction and production of minerals and metals needed for a low-carbon energy future. Current trends and projections suggest that the future low-carbon energy system will have greater material needs than the current one. Thus, it is important to better understand the full impacts of increased resource extraction to help ensure a sustainable and just transition. This review reveals that existing methodologies are currently insufficient in capturing the full suite of environmental, social, and governance concerns. The copper supply chain is used as a case study to highlight areas that require refined or augmented methodologies, with an in-depth examination of the corporate practices of Freeport-McMoRan, Vale, and BHP. Together, this review of existing methodologies and examples from the copper supply chain highlight the incomplete and variable nature of environmental and climate reporting within the mining industry. Areas for future work are defined with the goal of advancing accounting frameworks for the mining industry and the associated supply chain.

1. Introduction

While low-carbon technologies have become economically competitive over the past decade, they also have relatively high material needs and different environmental impacts than the current energy system. A steadily growing body of reports and forecasts examining the demand for materials required for the energy transition has shown that an unprepared extractive industry could struggle to keep up with rapid increases in demand, and in some cases exceed current reserves by 2050 [1–9]. In particular, an analysis by the World Bank of total mineral demand for renewable power and energy storage shows that up to 200 million tons of iron, 100 million tons of aluminum, and the 30 million tons of copper might be required for wind, solar, and battery storage alone [1]. Similarly, increases in demand for other minerals and metals used in low-carbon technology may also increase dramatically [10, 11]. Given

the global climate goals tied to 2050, meeting the mineral requirements for the energy transition is of key strategic importance.

While material estimates serve as a first-order indication of scale, economists, e.g. Tilton *et al* (2018), argue that material shortages will be short-lived (if at all), and Mudd and Jowitt (2018) argue that the key factors governing mining and mineral extraction are not physical in nature, but social, environmental, and economic [13, 14]. Following this and the strong relationship between developing economies and the extractive industry, Environmental, Social, and Governance (ESG) reporting has become a focal point for mining corporations looking to address a legacy of environmental degradation and the numerous environmental uncertainties surrounding increasing extraction of resources [11].

As there is no universally accepted or enforced international regulation, nor any global market driven certification schemes, the extractive industry

has turned internally to ESG propositions, sustainability reports, and other voluntary disclosures to relay ‘impact on critical sustainability issues such as climate change, human rights, governance and social well-being’ [15, p 1, 11]. Public acknowledgment of these concerns has led to calls for increased transparency from mining operations, but they are still not well understood [11, 16, 17]. Among these, environmental impacts are perhaps the most mischaracterized despite their strong relationship with social and governance considerations. Climate agreements and advocacy groups for renewable technologies have presented the environmental impacts of resource extraction as a global problem that requires global solutions. To this end, virtually every nation on Earth has adopted the Paris Agreement with the understanding that emissions can be quantified, controlled, and regulated [18]. Nations troubled by conflicts and extreme poverty have signed the agreement with the understanding that the global environment can be independent the numerous social and governance issues, and that developmental changes can be implemented. Ultimately, companies are responsible for making changes to align their operations with the Paris Agreement; the mining industry has played a role in these developments, but their ability to report on, yet alone address, these changes can no longer be considered adequate. While indicators and reporting systems exist for geological, technical, structural, political, regulatory, and economic supply risks within the industry, ‘there is currently no holistic method and information system for environmental concerns associated with the mining of raw materials’ [19, p 1].

With no universal methodology that can assess environmental impacts consistently for minerals and metals, how effective are the current frameworks at relaying relevant environmental concerns? How effectively are international environmental concerns being assessed and governed? What does this mean for the energy transition? To answer these questions, this review presents a problem-oriented perspective aimed at identifying gaps in the current reporting of environmental issues across the mineral and metal supply chains supporting the energy transition. Of specific concern are environmental impacts from extraction and production of minerals and metals.

Published ESG reports, greenhouse gas (GHG) calculation standards, reporting questionnaires, and academic literature were collected and evaluated to understand potential flaws and points of contention [1–97]. CDP reports for the 2018 reporting year formed the initial data source due to their consistent structure and organization. The reports chosen were based on mineral production quantities. Of the top ten copper producers, only six reported to CDP, and only five are members of the ICMM [42, 44, 88]. From these five companies, 2018 Global

Reporting Initiative (GRI) reports were used as secondary sources to compare required disclosure categories [89, 90–97]. Inconsistencies and changes in relative focus between companies and their reports were categorized and are outlined below. They were then further contextualized through full-length peer-reviewed academic papers comparing GRI reports, mining disclosures, and emissions from mineral sources. This review then focused on grey literature and white papers that were used within GRI methods, GHG protocol methods, and CDP questionnaires. From this, copper was chosen as a case study due to its critical role in renewable technologies, its production by many of the world’s largest mining companies, and its complex emissions life cycle. Unlike steel or aluminum production, which has its primary climate impacts on processing, copper has GHG emissions associated with extraction, hauling, comminution, and processing. Discrepancies among reporting methods and relevant background information were organized into effective categories to form the sections of this paper.

The remainder of the paper is structured as follows: section 2 reviews the current environmental impacts of mining. Section 3 evaluates the state of corporate mining reports. Section 4 analyzes what is generally included in reports, whereas section 5 discusses missing information along the supply chain. To put all of this into context, and also offer a timely empirical case study, section 6 evaluates copper’s representation on corporate mining reports. Section 7 concludes with areas for future investigation.

2. Current environmental impacts of mining

Environmental impacts from the mining industry include GHG emissions, ecotoxicity impacts, and human toxicity impacts, as outlined by the United Nations in their annual resources outlook report and figure 1 [12]. In the mining industry, these impacts primarily come from the common metals that account for >95% of global domestic extraction, namely iron, steel, aluminum, and copper [12]. However, the materials needed for the energy transition can compound these environmental concerns. With many renewable materials expected to rapidly increase in demand, new climate change impacts and toxicity sources are likely. It is therefore important to understand the potential environmental impacts of both common metals and specific materials needed for renewable technology.

Despite attempts at improved governance and better corporate management, procurement of many mineral and metal resources remains environmentally capricious and, in some cases, a source of conflict at the sites of resource extraction [20]. Due to lack of preventative strategies and measures, such as drilling with water and proper exhaust ventilation, many

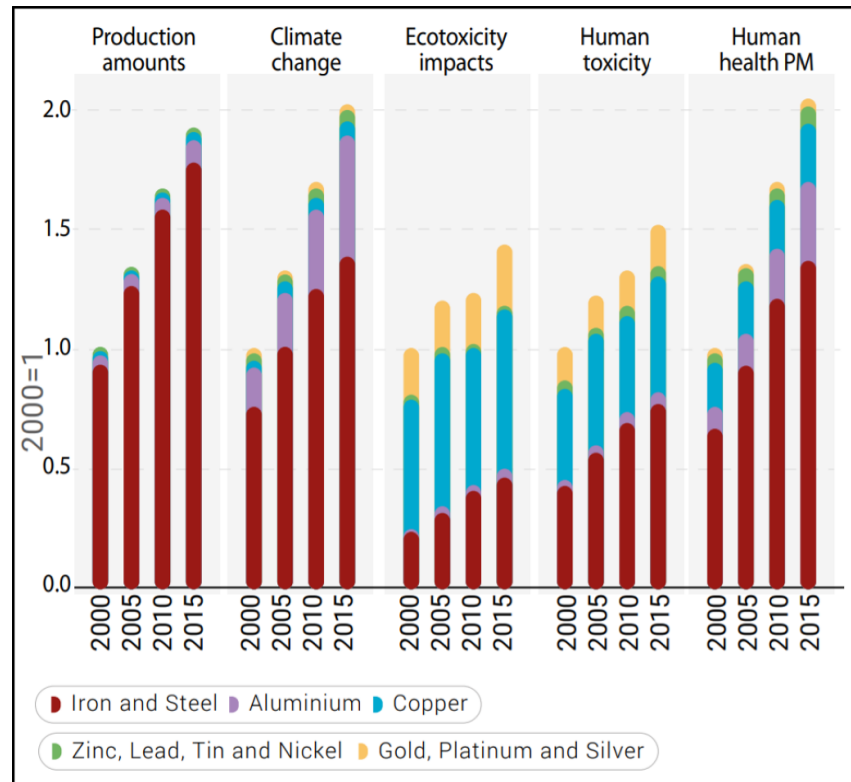


Figure 1. Metal production amounts and environmental impacts of metal mining and processing from 2000 to 2015 (selection of ten metals covering >95% of global domestic extraction of metal ores in 2015). Reprinted with permission from [12].

cobalt mines throughout the Democratic Republic of the Congo (DRC) contribute to deforestation, tailings pollution, landslides, dust, and fugitive emissions from diesel generators and trucks (figure 2) [21, 22]. Mining for copper, needed for electric wires and circuits, thin-film solar cells, as well as lithium, used in batteries, has been criticized in Chile for depleting local water resources across the Atacama Desert, destroying fragile ecosystems, and converting meadows and lagoons into salt flats [23]. The extraction, crushing, refining, and processing of cadmium, a byproduct of zinc mining, into compounds for thin-film photovoltaic modules that use cadmium telluride or cadmium sulfide semiconductors, can lead to groundwater or agricultural soil contamination, or worker exposure to hazardous chemicals (cadmium chloride), and occupational air pollution [24]. Rare earth minerals, such as neodymium, are needed for magnets in electric generators and motors, electric vehicles, and the fluid catalysts for shale gas fracking. But their mining in China has resulted in chemical pollution from ammonium sulfate and ammonium chloride that now threaten rural groundwater aquifers as well as rivers and streams [25].

Mining and metals processing also have substantial carbon footprints. Due to its large ore volumes and high processing needs, the global iron-steel production chain is already responsible for as much as 7%–9% of direct GHG emissions [27, 28]. When combined with aluminum's

high energy requirements and copper's processing impacts, the three metals have come to represent more than one-quarter of global industrial energy demand and associated emissions (figure 1) [12]. In consideration with other commonly produced minerals and metals, the climate (global) and health (local) impacts from extraction and production has nearly doubled between 2000–2015, and represent over 10% of global GHG emissions, and 12% of global particulate matter health impacts [12]. When including non-metallic minerals, the extractive industry accounts for as much as 20% of global GHG and 20% of global particulate matter emissions [12] (figure 1).

Looking at future trends, environmental impacts may grow, rather than recede, and large increases in mineral and metal demand specifically for the energy transition can compound environmental concerns (figure 3). The Institute for Sustainable Futures' report *Responsible Minerals Sourcing for Renewable Energy* explores some of these 'hotspots' [29, p 1], and found significant environmental impacts associated with the mining and processing of these metals [29]. For the 14 materials needed for renewable technologies that they explored, they found issues with large volumes of solid waste, harmful chemicals, heavy metal contamination (air, water, and soil), water shortages, tailing spills, and broader health impacts for workers and surrounding communities [29]. Increases in cumulative demand through 2050 for cobalt, lithium, and rare earths were found to be of specific concern due to the rapid growth of vehicle

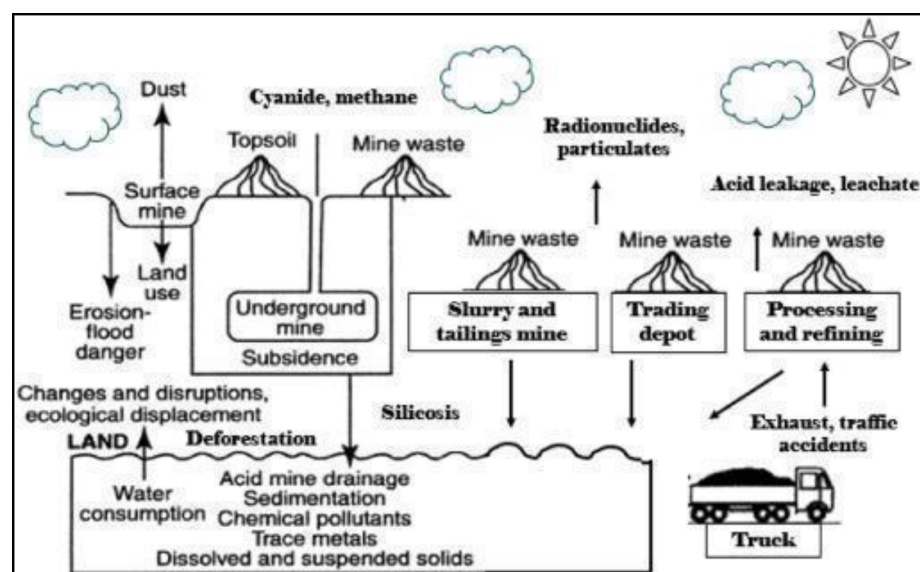


Figure 2. The multi-dimensional environmental impacts of copper and cobalt mining in the Democratic Republic of the Congo (DRC) [26]. Copyright © 2020, Elsevier.

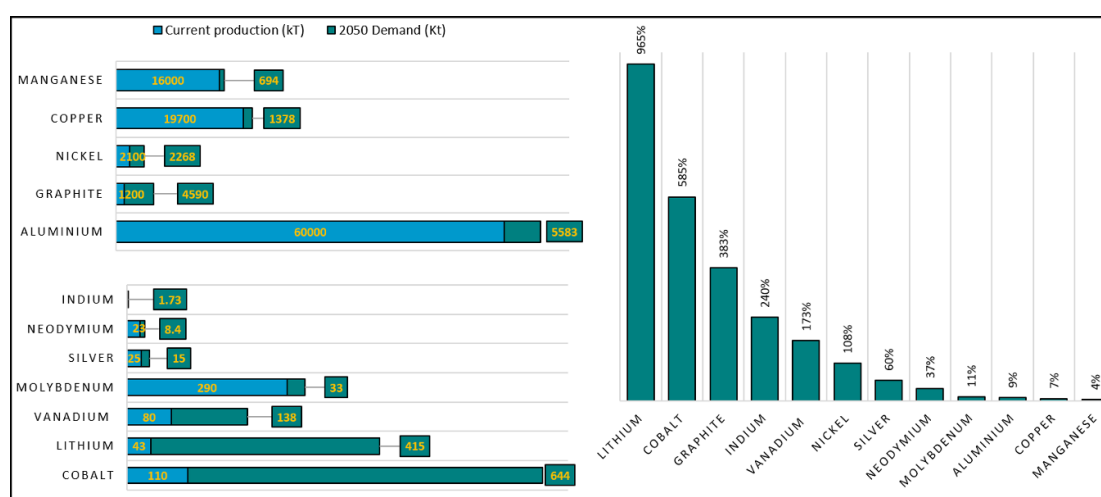


Figure 3. Mineral growth as a percentage of 2017 production to 2050 (only) [11].

electrification and the acceleration of battery storage technology (figures 4–6) [29]. For cobalt, 65% of the world's supply comes from the Democratic Republic of the Congo (figures 4–6), which has a history of environmental and social abuse, and is part of one of the ten most polluted places on Earth (African Copper Belt) [29, 30]. Rare earth elements (REEs) have also already caused significant problems in China due to toxic chemicals and the technologically-enhanced, concentrated, radioactive materials from REE processing and extraction [25, 29]. Lithium brine extraction, while less energy intensive than other processes, poses potential problems due to an expected 1000% increase in demand and the lack of long-term environmental investigations into the extraction's effects on one of the most arid locations on Earth [29].

The ability to track mineral and metal sources is also becoming increasingly relevant, both to

capture the full environmental impacts of a material, and because impacts are often disproportionately felt by developing countries. Increases in mineral demand present numerous opportunities for low-income countries focused on resource extraction and processing, but also can mean that operations may take place in environmentally sensitive areas such as forests, rivers, and coastlines, and sometimes without robust governance structures and regulations in place [31]. The 2017 Resource Governance Index found that across different minerals, on average, 37% of mineral reserves are in countries with a mix of strong and problematic areas of resource governance [31]. These problematic areas imply that resource extraction can help society, but it is likely that the eventual benefits to the surrounding areas will be weak [31]. A further 7% of minerals were in countries that have minimal procedures and practices to govern

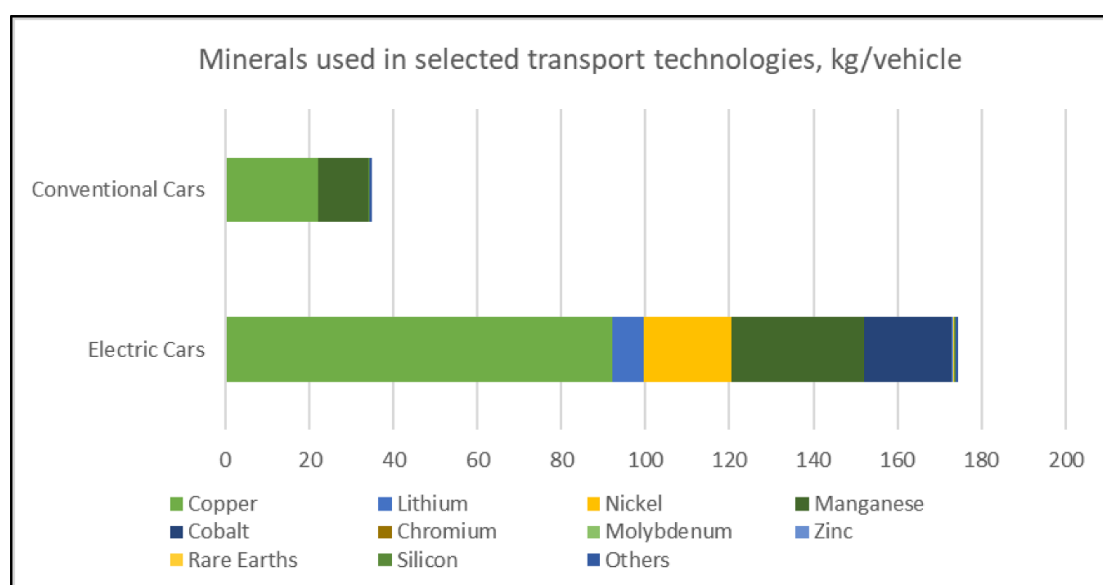


Figure 4. Minerals used in selected transport technologies [32].

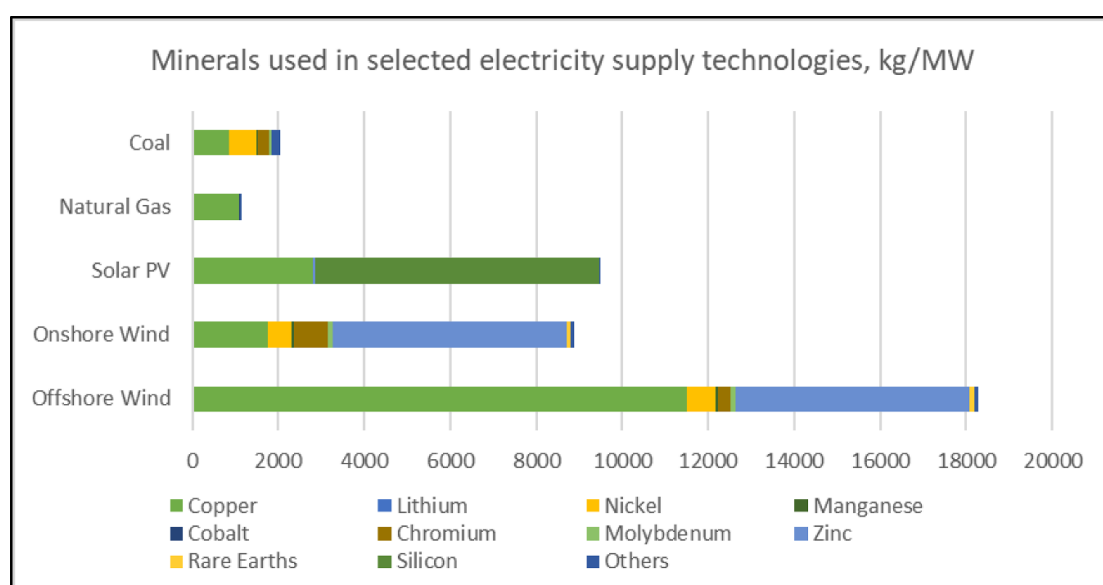


Figure 5. Minerals used in selected electricity supply technologies [32].

resources, where most of elements necessary to ensure societal benefits were found to be missing [31]. Countries with weak or poor governance are less likely to adopt policies that can benefit citizens, communities, environmental health, and mining operations [31].

McKinsey and Company's 2020 report on climate risk for mining companies warns of climate change hazards 'increasing physical challenges to mining operations' [33, p 1], with water stress and flooding being direct challenges that operators will need to overcome [33]. Analysis of the MineSpans database for copper, gold, iron ore, and zinc, found that 30%–50% of production already occurs in areas with high water stress, and that 'these hot spots will worsen in the coming decades' [33, p 3]. While

more capital-intensive approaches and water intensity reductions can help to mitigate negative effects, shifting demand for minerals, and calls for the industry to decarbonize, present their own problems. With coal representing 50% of the global mining market and 'the most obvious victim' [33, p 5] of shifts to global decarbonization, many mining companies will need to rebalance non-diverse mineral portfolios and begin considering the impacts of a circular economy [33]. Production of niche commodities can help to manage losses, but companies also need to look at decarbonizing through several operational levers (figure 7), with the understanding that 'building a climate strategy will not be quick or easy—but waiting is not an option' [33, p 1].

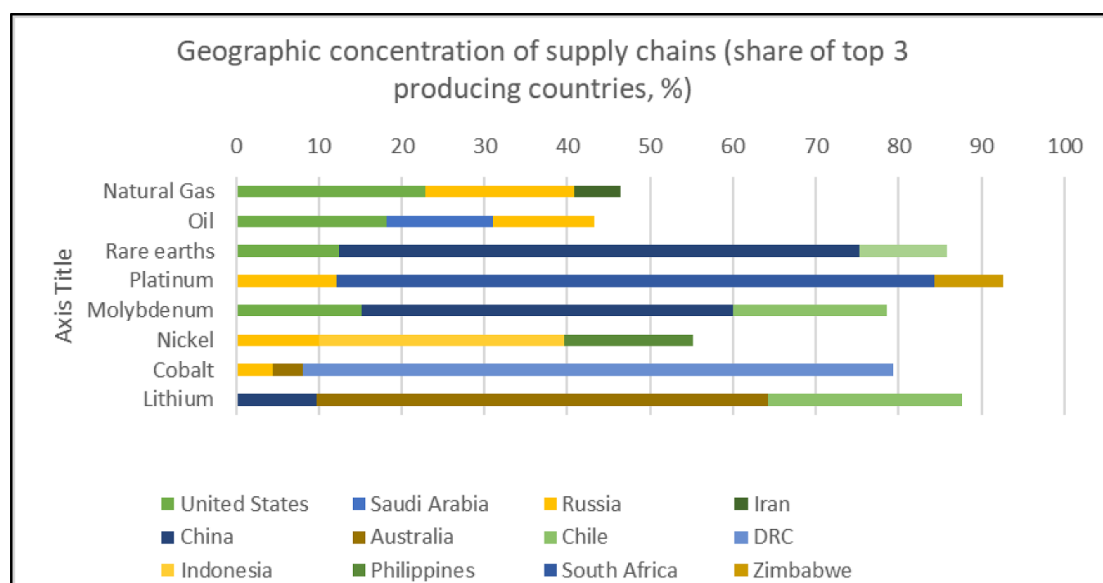


Figure 6. Geographic concentration of supply chains [32].

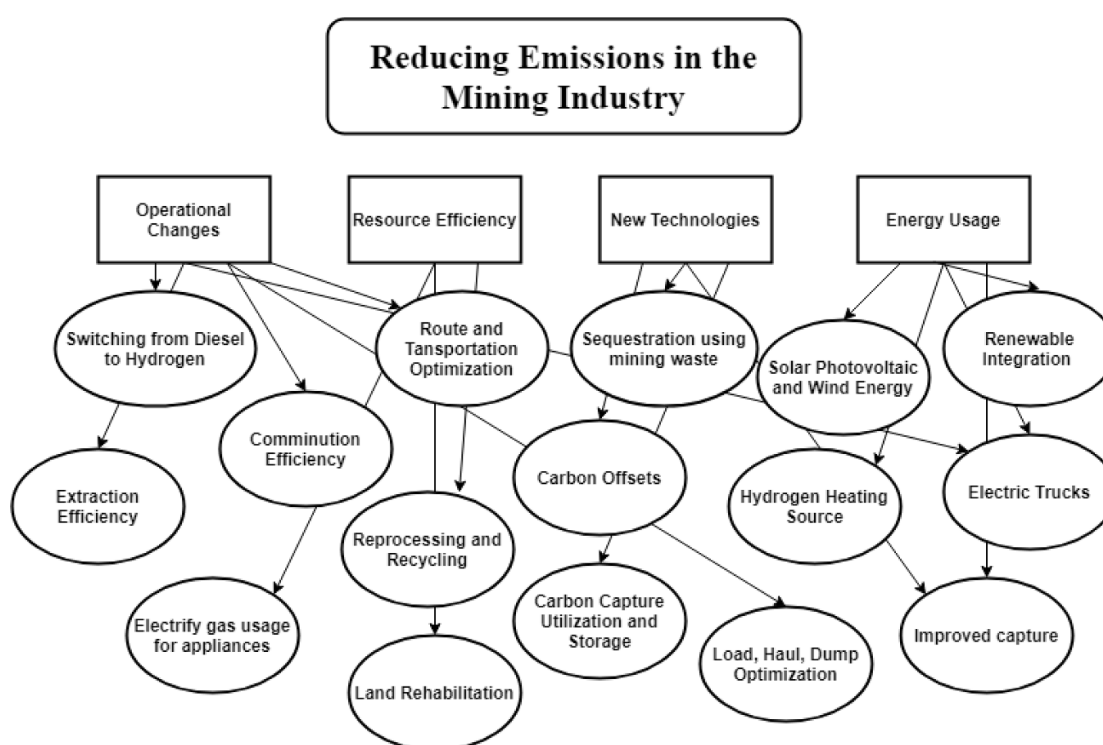


Figure 7. Pathways for mitigating the greenhouse gas emissions in mining [16].

3. Evaluating the state of corporate mining reports

3.1. Background

A mix of emerging sustainable development concepts being applied within industry, high ESG sector risk analyses (figure 8), and global commodity markets, have all resulted in increasing economic pressure for mining companies to report and reduce their environmental impacts. For example, a KPMG survey of

corporate sustainability reporting found that 93% of the world's largest 250 companies now publish sustainability reports, while the CDP claims that over 8400 companies have reported through them regarding climate change, water security, and forest health [34, 35]. A core tenet of the literature on corporate social responsibility is that private firms must not only meet their fiduciary responsibility to shareholders and their legal responsibility to avoid fraud and illicit activities; they must also promote a broader

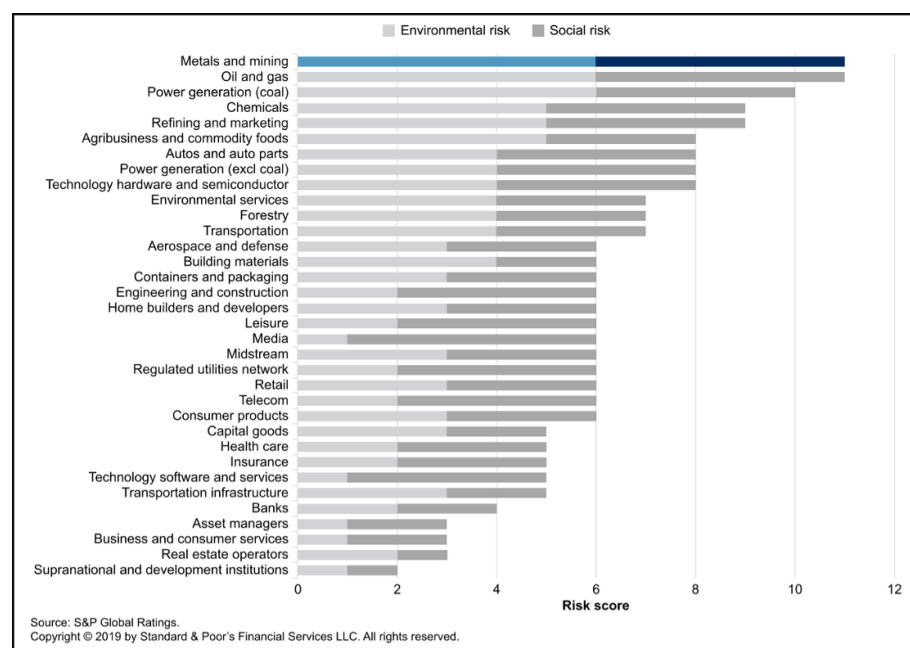


Figure 8. ESG sector risk analysis. Reprinted with permission from [39].

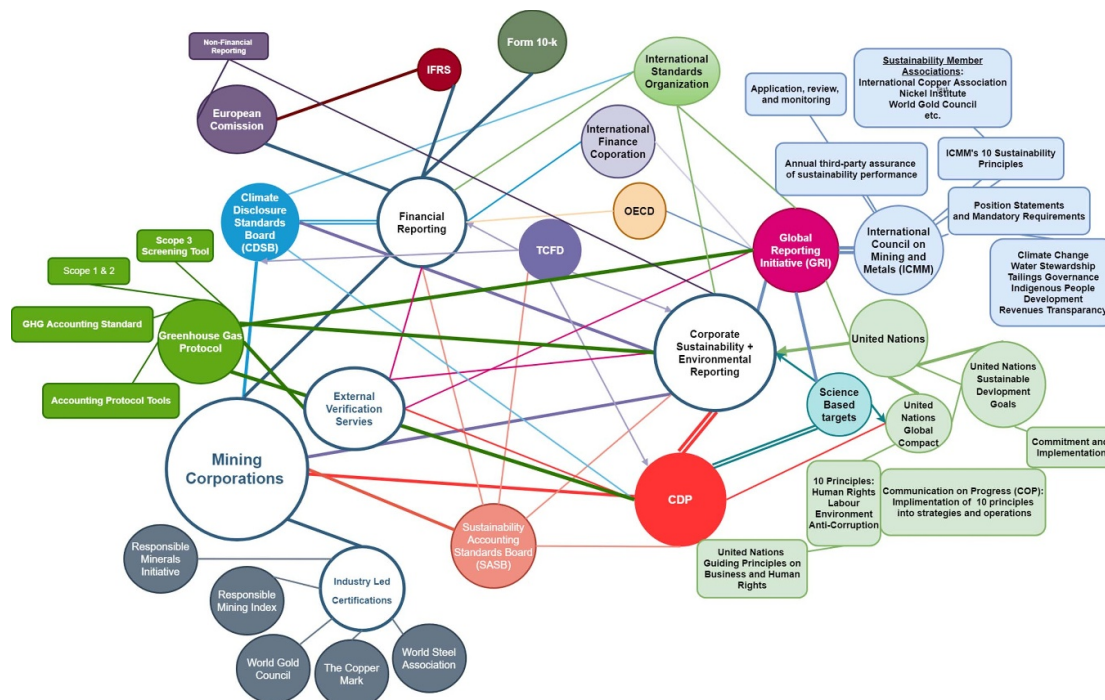


Figure 9. Mining company reporting relationships and requirements.

social agenda. This agenda frequently includes facilitating the prosperity of communities, minimizing environmental degradation, and contributing to the creation of safe and peaceful societies with strong institutions and equitable distribution of costs and benefits [36]. Gallarotti (1995) even suggested, writing more than two decades ago, that the business community was beginning to shift towards 'green consumption,' [37, p 43] a transition that had the

potential to create 'a new business ecosystem' [37, p 50] enhanced by the principles of human rights, transparency, and sound governance [37].

For the mining industry, their substantial role in sustainability reporting began after an economic and social crisis in the mid-to-late 1990s which threatened the industry's 'social license to operate' [38, p 1], and resulted in the creation of the International Council of Mining and Metals (ICMM) [38].

Following its formalization in 1999, the Global Mining Initiative (soon to become the ICMM), began working closely with the Global Reporting Initiative (GRI) to develop a reporting supplement aimed at ‘a clearer understanding of the positive role the mining and minerals industries can play in managing the transition to sustainable development’ [38, p 18, 40]. Membership to the ICMM now requires that companies report their sustainability impacts in accordance with the GRI’s Mining and Metals Sector Supplement, and seek independent assurance of their reports [41]. The ICMM now includes 26 of the world’s largest mining and metals companies, and 35 associations aimed at addressing ‘the core sustainable development challenges faced by the industry’ [42, p 1]. The mining industry has also started reporting to independent organizations such as the CDP, Science Based Targets (SBT), and Task Force on Climate-Related Financial Disclosures (TCFD), who help structure sustainability reporting and maintain the disclosures as a primary source for a company’s ESG developments.

3.2. Numerous reporting initiatives and standards

The GRI and other reporting frameworks are meant to measure relevant environmental indicators, but corporate reports by the mining industry are not standardized and often struggle to weigh relevant inclusions and explanations. The numerous changes in reporting requirements (figure 9) have progressed through consumer/investor pressures to use disclosure programs that offer unique insights and indicators for specific environmental impacts or concerns related to the energy transition [42–45]. CDP’s quantitative focus is meant to simplify and standardize GHG emissions reporting while empowering ‘investors, companies, cities, and national and regional governments to make the right choices... for people and planet in the long term’ [35, p 1]. The TCFD aims to ‘help firms understand what financial markets want from disclosure in order to measure and respond to climate change risks’ [46, p 1]. A company’s GRI guided sustainability report is meant to ‘demonstrate(s) the link between its strategy and its commitment to a sustainable global economy’, and promotes ‘climate change, human rights, governance and social well-being’ [15, p 1]

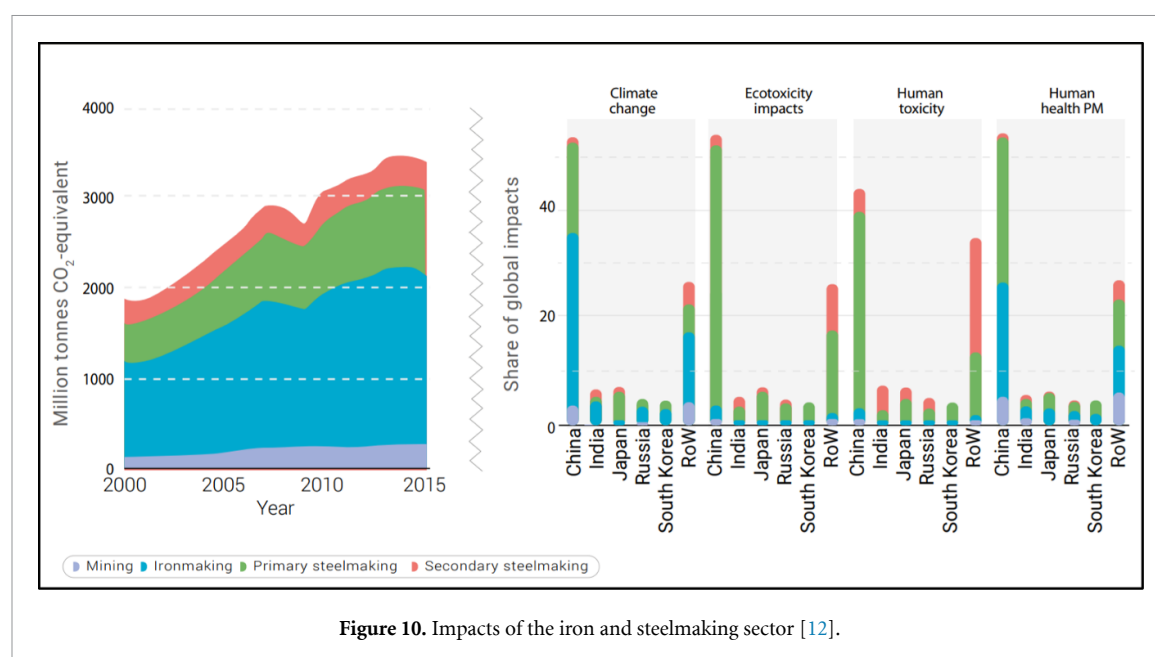
The issue with these developments is that there is no underlying framework to identify the specific interactions between the mining industry and the environment, or to enable the selection and operationalization of the most relevant environmental indicators [47]. Each initiative varies in status (legal requirement vs. voluntary disclosure), scope (climate vs. impacts), and ambition (discourse vs. strategy), which is meant to present an encompassing picture of ESG developments, but instead forces companies to focus on specific ‘silos of sustainability’ within their organization and balance what is relevant for specific

disclosures and what is financially best for their company [47, 48]. Depoers *et al* (2016) illustrates this point in its study of SBF 120 (Société des Bourses Françaises 120 Index) firms, where it was found that managers adapt their disclosure strategy to address the information needs of different stakeholder groups by changing sources, traceability, and inclusions [49]. In promoting the analysis of dozens of indicators that neglect interactive effects and ‘the state of the socio-ecological systems from which they are drawn’ [47, p 73], there is an overt emphasis on individual metrics and not a company’s actual sustainability practices [47].

This focus on individual metrics and general indicators can be seen at the end of almost every published sustainability report, where mining companies provide content indices on what metric was addressed, the response, the page number it can be found, what sustainability principles it was supposed to meet, if it has external assurance, and why it counts as a sufficient response. This is especially relevant for the extractive industry, where the sale of anonymous, primary goods creates the ‘essential conflict between financial and other bottom lines, which, for the foreseeable future at least, the financial will always win’ [47, p 72, 50]. With no market differentiation, and operating under a collective industry reputation, the appearance of sustainability becomes just as valuable as actual practice. This often leads to companies to report with numerous initiatives, without the additional initiatives having dramatic effects on reporting. Mark Carney, Chairman of the Financial Stability Board, conveyed this best when introducing the TCFD in 2015 [51]. With nearly 400 initiatives aimed at relaying the costs, opportunities, and risks associated with climate change, meeting effective disclosure standards requires coordination, and ‘the existing surfeit of existing schemes and fragmented disclosures means a risk of getting ‘lost in the right direction’ [51, p 1]. Similar challenges exist within the Extractive Industries Transparency Initiative (EITI) which seeks to foster accountability and minimize corruption in the oil, gas, and mining sectors, but often has mixed outcomes in its ability to promote broader improved governance or sustainability [52, 53].

3.3. Comparability

The lack of contextualized disclosures for the mining industry limits sustainability reporting initiatives, and users of their data, in their ability to convey a company’s progress towards sustainability. Constructive critiques of reporting methodologies specifically cite the lack of guidance for geographic variations, scales, and interactive effects as major drawbacks [47]. These are especially prominent when considering the environmental impacts of different production routes, as they can reflect everything from



‘ore mineralogy and grade, mining type and available technologies, to resources for the mining and processing’ [16, p 100]. Further, with a large number of multinational feed streams, waste streams, by-product streams, and energy inputs associated with mining and processing, reporting frameworks are not capable of characterizing the entire supply chain of a mineral, or of specific production challenges. For the energy transition in particular, it is especially necessary to be aware of environmental reduction levers (figure 7), including the feasibility of adopting renewable technologies, and the regional energy mixes.

The scope and scale of environmental concerns is not limited to minor metals, but also to minerals and metals with established markets. For the steel industry, with a large global production chain, these influences can be seen in figure 10. For example, the United Nations Global Resources Outlook reported that the first processing step in the primary production of steel accounts for more impacts than the iron ore extraction phase for all reported indicators, and the climate change impacts for secondary steel production can vary as much as 10%–38% due to the electricity mixes between countries (figure 10) [12]. This has led many companies to attempt to curb their Scope 3 emissions, both upstream and downstream. For companies like Rio Tinto, who sell large amounts of iron ore to China, they have attempted to curb their Scope 3 emissions by pledging \$400 million to help reduce their customer China Baowu Steel Group’s emissions [54]. They hope to reduce their own supply chain emissions through their clients use of less metallurgical coal, transportation optimization, and possibly the unproven commercialization of hydrogen steel [54]. These changes and developments are in contrast to reports by American copper producing companies who state that truck haulage

is a focused concern for both cost and GHG emissions, and that through site development and falling ore grades, ‘trucks are required to move ore farther distances to processing facilities’ [55, p 26, 56]. With different focuses on environmental concerns and different reduction levers (figure 7), using generalized reporting initiatives to compare environmental pathways and emission reductions is not comprehensive. In the context of global production networks and international supply chains, the dismissal of holistic and systemic perspectives diminishes comparability and assessment of progress [47, 57].

3.4. Quantitative comparisons

The lack of contextualized disclosures can limit comparability between sustainability pathways, yet more focused and quantitative guidance can also fail to encompass relevant environmental considerations. Investigations into comparing quantitative aspects of sustainability reports for mining and processing companies have found that ‘it is impossible... in a credible manner’ and not useful ‘to classify firms on this basis’ [57, p 25]. Henri and Boiral’s 2015 study of mining sustainability reports compared only A or A + GRI reports (the highest rated) and still ran into issues including:

- Measuring unmeasurable or unspecific information.
- Comparing incomparable measurements.
- Interpreting incomplete or ambiguous information.
- Analyzing opaque or self-proclaimed reports.

The study found that ‘less than 50% of all GRI indicators focused on quantitative measurements,’ [57, p 16] while the rest were unmeasurable and

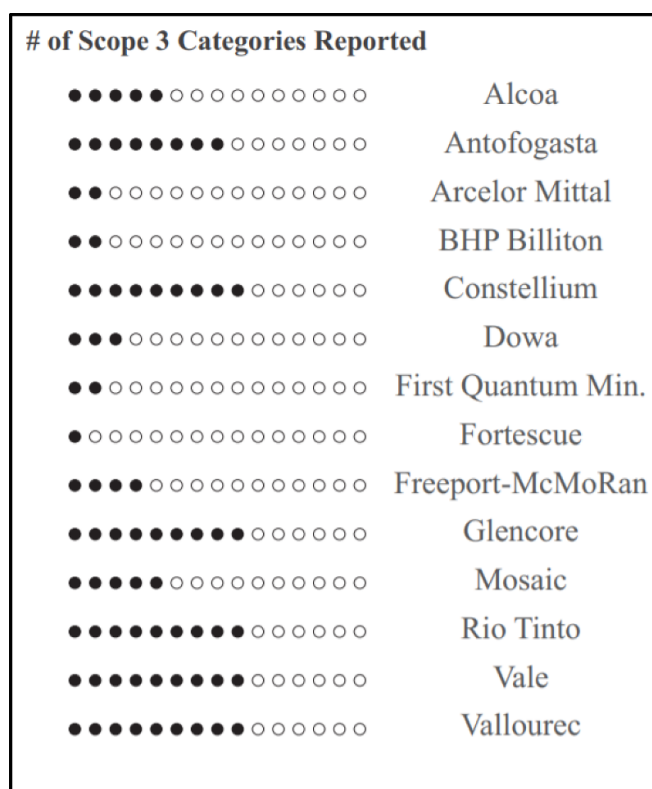


Figure 11. An overview of the number of Scope 3 emissions categories reported for 2015 CDP reports [17]. © EDP Sciences, 2018.

unspecific [57]. The result was a sea of words or ‘tower of Babel syndrome’ [58, p 1] that makes it difficult to interpret differentiating criteria while giving firms a great deal of freedom in how they responded and what they presented [57, 58, p1]. Critical information, such as weight of transported hazardous waste, was often incomplete or completely absent, while companies like Codelco wrote as much as 20 pages on renewable energy, salmon farming, and educational projects in Chile (2008), and Newmont more than 60 pages on the firm’s sustainability management system [57].

The complications of having accurate, topical, and substantive measurements were further exacerbated by the existence of several affiliate organizations and different levels of data aggregation, even among single reports. Companies such as Rio Tinto were able to disclose information both with and without Alcan (a subsidiary purchased in 2007) depending on the indicator they were reporting, all while maintaining an A or A+ reporting score [57]. Even among CDP reports, Andre and Cortese (2012) examined disclosures of metals and mining companies operating in the Australasian region to determine whether voluntary information can provide a meaningful basis for climate change related decision making [59]. While acknowledging the important work the CDP undertakes, the combination of various disclosure methods, and the absence of emissions data, compounded difficulties and led

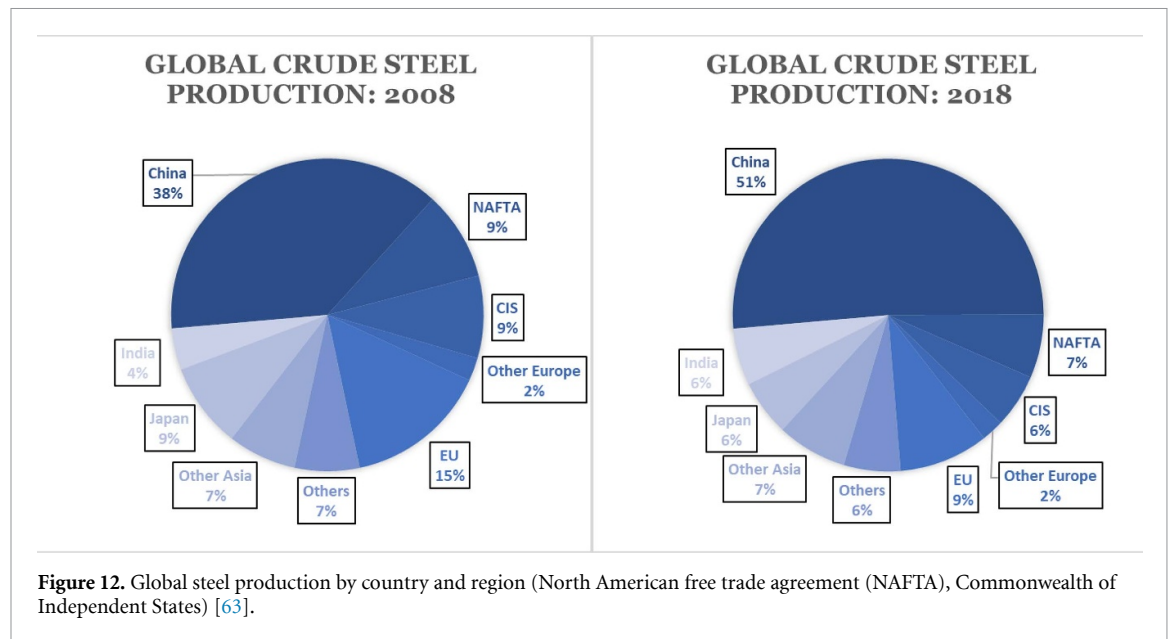
to the conclusion that ‘the CDP information is not comparable, and by extension, limited in its usefulness’ [59, p 14].

4. Common evidence and themes within the literature

Notwithstanding these drawbacks, corporate mining reports serve a significant purpose. In this section we show they do establish a common ground for evidence, albeit emerging and often incomplete, on CHG emissions, life-cycle assessment (LCA)-based calculations, and impacts in developing countries.

4.1. GHG emissions

Whereas calculation standards, protocols, and methodologies are well established for Scope 1 and Scope 2 emissions, the recent interest in Scope 3 emissions has presented a challenge in accurately mapping and reporting GHG from global supply chains. The Greenhouse Gas Protocol Corporate Value Chain (Scope 3) Standard provides guidance and evaluation tools for Scope 3 emissions, but companies are still allowed to choose what values to report, the boundaries for emissions categories, and even what categories they consider relevant. Looking at figure 11, no mining company reported more than nine categories in 2018, with other inclusions being written off as not relevant [17]. Greene (2018) highlights the difficulties of comparing selective disclosures in her study



of CDP reports and Scope 3 emissions stating that ‘incomplete reports make it difficult to track emissions reduction goals or implement sustainable supply chain improvements’ [17, p 1]. These inclusions are especially relevant when considering that ‘emissions reported by one company operating at one stage of the life cycle contribute to the value chain emissions of another,’ [17, p 7] and that GHG emissions from the value chain can amount to over 90% of total emissions for some companies [17].

Reported values become even more convoluted when considering that companies rely on default data to obtain their values and emissions factors, since supplier data is often difficult to obtain [47, 17]. For minerals and metals specifically, being a commodity with long life-cycles and further processing needs means that most reporting companies have to make assumptions for end product uses and general processing routes. This often means assuming a conversion factor for ore feedstock, that all ore is converted to metal, and that all produced metal has the same emissions factor. These values can vary greatly depending on life-cycle assumptions, where a product is sold to, and the purchasing companies own subsequent emissions and policies.

4.2. LCA based calculations

With supplier data difficult to obtain, and global value chains becoming increasingly complex, many reported values are based off of LCA, which have their own caveats related to supply chains, metrics, and function. The use of LCAs as a tool to promote the sustainable design and redesign of products and processes is part of what has led to the adoption of renewable technologies and positive environmental changes in the mining industry. However, ‘LCA is a relative tool intended for comparison and not absolute evaluation,’ [60, p 1] which can limit its effectiveness

in supporting environmental disclosures and representation of entire supply chains [60]. While data on global warming potential and energy inputs are well documented in life cycle inventories (LCIs), ‘other relevant impacts resulting from, e.g. acidification, heavy metal emissions, water or land use are fragmentary’ [19, 93]. Nuss and Eckleman’s 2014 LCA of 63 metals in their major use forms was the most comprehensive life cycle comparison of metals to date, but ‘impacts other than global warming potential and cumulative energy demand could not be further investigated ... due to the limited availability of life cycle inventory data’ [19, 61, p 4]. Nuss and Eckleman (2014) also states problems with LCI data being reported in aggregate form at ‘either pre-allocated or at system process level,’ [61, p 2] which makes it difficult to make robust comparisons or to take co-production issues with minerals and metals into account [61]. Co-production is especially important for the energy transition as many of the materials needed for renewable technologies occur as secondary minerals that are embedded in base metals (including rare earth’s, indium, and tellurium) [62]. Manhart *et al* (2018) also warns that major obstacles for assessing the life-cycle environmental relevance of primary raw materials are the lack of ‘representative data for the mining sector on a global level’ [19, p 94] and ‘the current lack of scientifically sound models for input categories on resources, which are particularly relevant for mining’ [19, 93].

These LCA considerations are apparent in the steel and lithium industries and highlight the need to consider entire supply chains. Greene (2017) conveys some of these shortcomings in writing that life cycle data commonly used in the steel sector is based on a small set of studies and geographic regions, and that the World Steel Association’s choice of boundaries can leave out important emissions [17, 64]. The

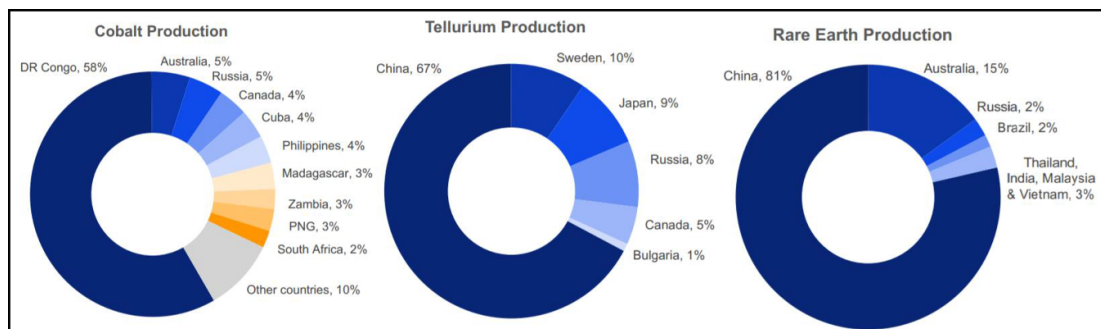


Figure 13. Concentrated mineral supplies for cobalt, tellurium, and rare earth elements [29]. © UTS 2019.

World Steel Association (WSA) reports 1.83 tonnes CO₂/tonne crude steel cast (2017), (the same value used by BHP's methodology in 2018), and uses indicators from '85 steel companies ... representing 56% of global crude steel production' [65, p 1]. With China representing 51.3% of global steel production (figure 12), coal supplying 75% of energy demand for global steel production, and China being one of the world's worst coal users and polluters, it can be hard to evaluate how representative aggregate values like these are, or how efficiently they can be used in reporting, without considering emissions intensity by geography [63, 66, 67]. For steel specifically, a 2016 comparison of carbon dioxide emissions intensity of production methods between various countries found that 'if the German, Mexican, and U.S. steel industries were similar in structure to the Chinese steel industry... the CO₂ emissions intensity of steel production in Germany, Mexico, and the U.S. would increase by 19%, 92%, and 56%, respectively' [68, p 16]. Together these variations show that LCAs need to be taken in context, but that they can also provide valuable insights into supply chains and possible points of intervention for environmental sustainability.

4.3. Environmental impacts in developing economies

Sustainability reports are meant to disclose negative environmental impacts in any developing economy, but this process has become increasingly convoluted. In the past, well publicized environmental disasters led to the ICMM 'crisis,' [42, p 1] and for mining companies to position themselves as drivers of sustainable development in emerging economies [38, 40, 69, 70]. The agreement that multinational mining companies should operate in accordance with international environmental standards, despite the lack of regulatory enforcement in developing countries, assuaged concerns that multinational mining corporations might exploit people and resources [40, 71, 72]. This is once again becoming a major concern due to the geographic concentration of minerals and metals for the energy transition, and their

subsequent vulnerability to price fluctuations and detrimental environmental/social practices. This has already been seen in the DRC with cobalt and REEs in China, and further concentrated supply of cobalt, rare earths, and tellurium can be seen in figure 13 [29]. Australia, the DRC, and South Africa have large shares of the production of metals for Li-ion batteries [29]. Japan, Korea, Canada, and Russia have significant production levels of metals for photovoltaics, while Chile, Argentina, and Peru have over half of the world's lithium [29, 73].

Impacts in developing countries are still under-reported, despite the numerous published projects and initiatives by mining companies. True Footprint's analysis of annual reports from 23 mining companies found that 70% of material indicators used for reporting were of inputs and outputs (how much was spent, how many natural resources were used, what activities were conducted), while only 26% explained the actual outcomes, and 4.5% the impacts [34]. The same analysis showed that it was possible to report outcomes for all material sustainability topics, but that companies chose not to, despite the outcome being potentially positive in some cases, as it was not required for reporting [34]. A study by Boiral (2013), found sustainability reports to mainly be a 'simulacra,' [74, p 1] due to their disconnect from reality, the distortion of information, and the use of images that were not considered relevant [74]. The 'emphasis on the firm's positive achievements,' 'emphasis on virtuous statements and commitments,' and 'showcasing of outside awards and distinctions,' [74, p 25] limited their reliability in conveying relevant information, while pictures of unspoiled nature and stewardship led to further misrepresentation [74]. The counter accounting analysis showed that 'only 10% of significant news events concerning sustainable development were reported clearly and explicitly in the sustainability reports,' [74, p 25] while the proliferation of images were largely disconnected from the firms' genuine impacts [74]. For developing countries, this presents a false image of sustainability and progress.

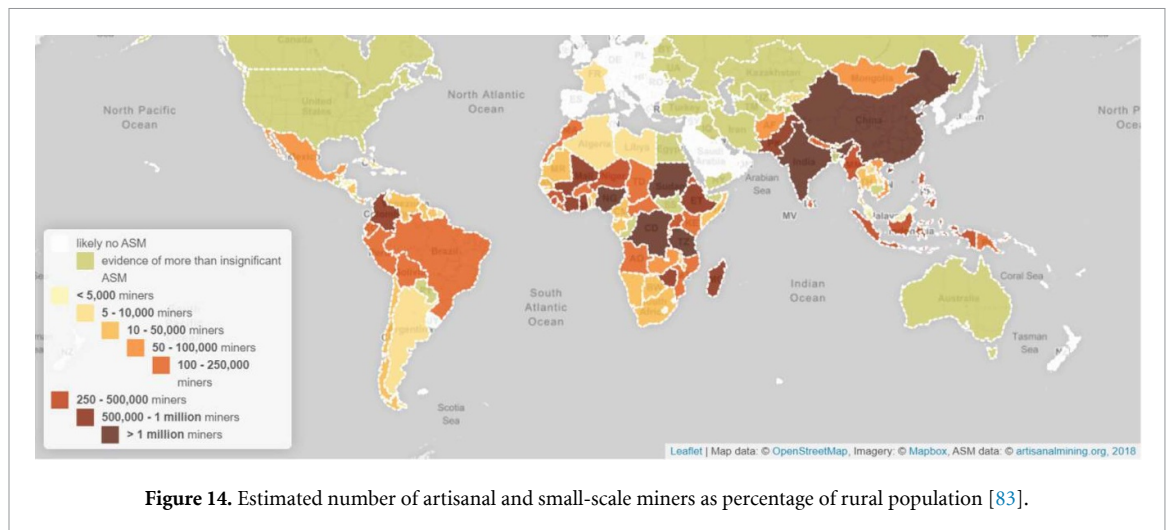


Figure 14. Estimated number of artisanal and small-scale miners as percentage of rural population [83].

5. Common lacunae and missing information within the literature

While the common themes of included evidence are perhaps striking, just as significant is what is missing within the body of evidence, notably gaps in environmental reporting, scant focus on artisanal or small-scale mining, and an inability to capture illegal or criminal supply chains.

5.1. Gaps in environmental reporting within sustainability reports

Sustainability reports, and most environmental methodologies, do not include unreported, unregistered, or even illegal mineral and metal production, despite the large role that they play in global supply chains and environmental impacts. Introduction of these materials primarily occur at the beginning of the supply chain following extraction and prior to processing. The growth of artisanal or small-scale mining (ASM) is already an environmental concern for developing economies, even without the large increases in demand for minerals and metals that is expected with the energy transition. There are an estimated 40.5 million people engaged in ASM in 2017, up from 30 million in 2014, 13 million in 1999, and 6 million in 1993, compared to the 7 million working in industrial mining in 2013 [75]. With the majority of ASM workers using rudimentary tools and techniques, there are significant health and environmental impacts associated with their operations. Among environmental concerns are fine particles from blasting and drilling that degrade crops and farmland, streams and rivers becoming toxic, and exposure to mercury, zinc, vapor, cyanide, and even radioactive materials [25, 75]. Scientific American's list of toxic pollution problems lists mining related activities as responsible for three of the top ten global issues, with mercury pollution from artisanal mining as the worst global toxic pollution problem [76]. While gold is

not as tied to renewable technology as other materials, large price increases for renewable materials have already seen similar spikes in artisanal mining operations.

5.2. Artisanal and small-scale mining enterprises

Existing examples of these practices and their environmental implications can be seen in parts of Africa and China [77–79]. Fortunes 2018 report, *Blood, Sweat, and Batteries* shows what increased prices for cobalt can do to insufficiently supported communities, while in 2019 the death of 43 miners once again demonstrated the impact of cobalt mining in the DRC [77–80]. Reports have found as many as 255 000 artisanal miners for cobalt in the Democratic Republic of the Congo, 35 000 of who are children working in 'exceedingly harsh, hazardous, and toxic conditions' [79, 81, p 1, 82]. As for where these materials go, the Chinese middle men haggling over cobalt prices in Mosomp cobalt market, and the children in a small village near Kolwezi greeting reporters with 'Ni hao!' [79, p 1] implicates China, the world's largest consumer of metals [79].

5.3. Illegal or criminal supply chains

Investigations into rare earth supply chains have found that illegal sources can add as much as 40% of official Chinese production, the results of which are tied to 'enormous social and environmental problems' [84, p 6744]. Due to rare earth mining in Jiangxi province, the region is facing a \$5.5 billion cleanup bill, with a focal point of the cleanup focusing on keeping the polluted water from reaching a wider area in neighboring provinces [25]. Ma Jun, a leading Chinese environmentalist, and director of the Institute for Public and Environmental Affairs, says that he fears other regions around the world could suffer a similar fate if they become like China, and are the supplier of cheap rare earth elements with little or no environmental price attached [25].

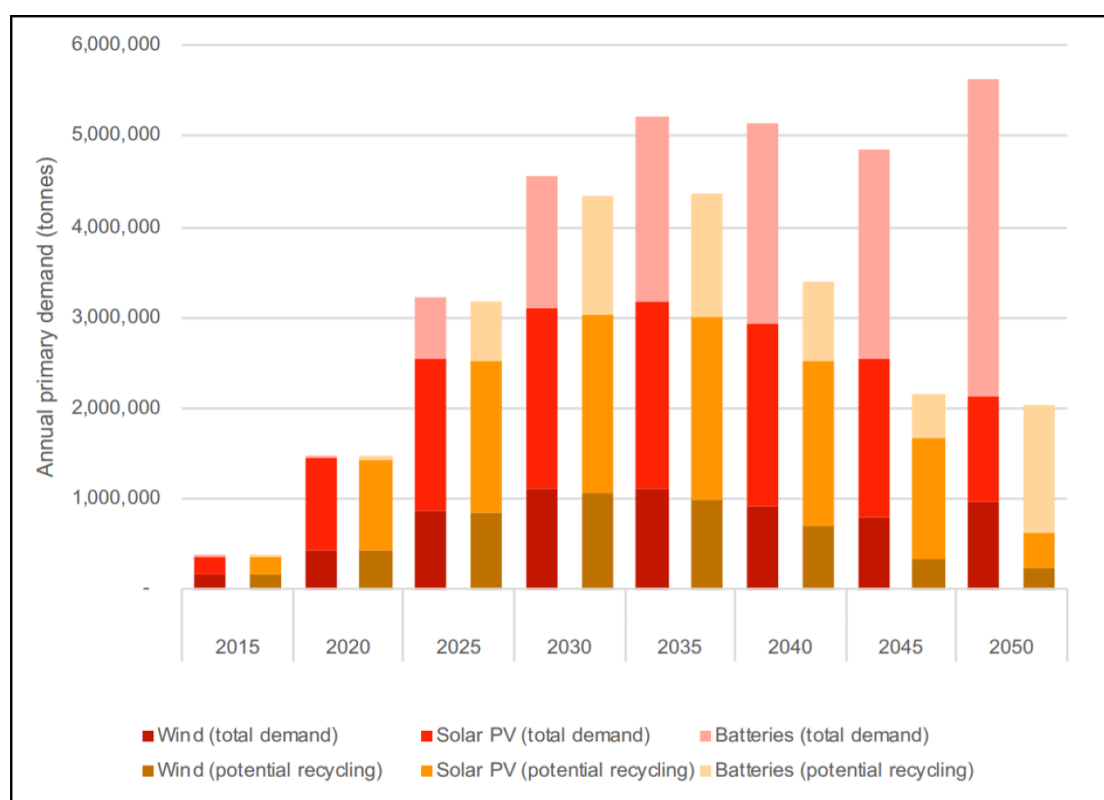


Figure 15. Share of primary demand for copper from wind, solar, PV, and batteries [29]. © UTS 2019.

These concerns over legal and accountable supply chains are very real, with ASM taking up entire percentages of populations (figure 14), and believed to account for 15%–20% of global non-fuel mineral production [75, 84]. With mining corporations only reporting on their own operations, LCA's not accounting for external variables, and supply chains getting partially fueled by unreported ASM, environmental impact methodologies are once again proving to be non-inclusive. Minerals and metals are entering supply chains, but not being properly accounted for in a global context.

6. A case study in corporate governance: copper

In this section, to illustrate the tensions and challenges with corporate mining governance reported in the earlier sections, the GHG emissions as reported by copper producing companies are compared to evaluate environmental impact methodologies. GHG emissions are used due to their quantitative and comparable nature.

6.1. Copper as an exemplar for low-carbon transitions

Copper's role in both conventional and low-carbon energy transitions is well established through conventional motors, wiring, and circuitry to its substantial use in wind turbines, solar, panels, and

energy storage technologies (figure 15) [1, 85, 86]. Estimates by the Institute for Sustainable Futures show that peak annual demand for copper in renewable energy and storage could account for as much as 29% of annual production by 2050 (2017 data) [29]. Copper is representative of numerous minerals and metals by demonstrating environmental concerns along numerous points throughout its lifecycle. Unlike steel or aluminum production, which have a large environmental focus on processing, copper has GHG emissions from extraction, hauling, comminution, and processing, which makes it representative of a greater number of GHG emissions from other minerals and mining practices. Calls for emissions transparency by Azadi *et al* (2020), and copper's historical role as an environmental polluter, make it a valuable case study to assess environmental impact methodology [16]. To ensure consistency in evaluated impact, only the reported GHG emissions will be compared for copper mining entities.

6.2. Calculating the environmental impacts of copper

Of the top ten copper producers, only six reported to CDP, and only five are members of the ICMM [42, 44, 88]. From these five companies, BHP, Vale, and Freeport were chosen to represent varied CDP and GRI reporting scores (table 1), and as an indication of completion. For 2018, all three companies created sustainability reports following GRI guidelines,

Table 1. Reporting scores for BHP, Freeport, and Vale.

Company	2018 CDP Score	2019 Score	Preparedness for a Low-Carbon Transition (rank) [87]	ICMM Membership	GRI
BHP	A	A-	#3/12	Founding Member	In accordance—Comprehensive
Vale	B	B	#1/12	Rejoined 2017	In accordance—Comprehensive
Freeport-McMoRan	C	F	#11/12	Founding Member	In accordance—Core

Table 2. Scope 3 and embodied emissions in copper, iron ore, metallurgical coal, and energy coal base (based on BHP data).

Scope 3 GHG emissions by category and material (2018)				
	Copper	Iron Ore	Metallurgical Coal	Energy Coal
Scope 3 GHG emissions (million tonnes CO₂-e)				
Upstream				
Purchased goods and services (including capital goods)	0.033283943	6.288284674	2.424304716	0.267714631
Fuel and energy related activities	0.005682624	1.073609579	0.413905683	0.045707376
Upstream transportation and distribution ⁽¹¹⁾	0.014612463	2.760710345	1.0643289	0.117533253
Business travel	0.000405902	0.076686398	0.029564692	0.003264813
Employee commuting	0.000405902	0.076686398	0.029564692	0.003264813
Downstream				
Downstream transportation and distribution ⁽¹²⁾	0.020295087	3.834319923	1.478234583	0.163240629
Investments (i.e. our non-operated assets) ⁽¹³⁾	0.00690033	1.303668774	0.502599758	0.055501814
Processing of sold products⁽¹⁴⁾	5.2	317.4		0
Use of sold products			112.3	71
Total Share of Scope 3 emissions (million tonnes CO₂-e)	5.282	332.814	118.243	71.656
Tonnes of Scope 3 CO₂-e per ton of material	4.267	1.423	2.906	2.458
Tonnes of Scope 2 CO₂-e per ton of material	3.183	0.001	0.026	0.003
Tonnes of Scope 1 CO₂-e per ton of material	1.123	0.008	0.131	0.016

reported to CDP's Climate Change 2018 questionnaire, and had third party verification for their emissions values [89–91]. As such, CDP and GRI-guided sustainability reports from BHP, Freeport-McMoRan, and Vale were used as the data source for this case study. Comparison of GRI reports, CDP reports, disclosed emissions factors, emissions sources, and reporting requirements were used to effectively compare reporting methods. From this, discrepancies and misalignments were focused on and elaborated in the sections below.

BHP is used as a *best case* scenario due to the external publication of a supplementary *Scope 3 Emissions Calculation Methodology 2018*, and separate GHG data [92, 93]. Through these published supplements, the embodied emissions in one ton of copper was calculated with the assumption that percentage share of mined material (by weight and excluding petroleum) was reflective of percentage share of the upstream reported Scope 3 emissions (table 2). From these assumptions, the resulting calculated Scope 3 emissions factor was found to equal 4.27 tonnes CO₂e per ton of copper produced by BHP. Calculated Scope 3 values were then added to BHP's Scope 1 and Scope 2 values to get the total emissions for one ton of copper produced by BHP and accounted for by their methodology. Using BHP's new calculated emissions

factor, the reported production values and emissions of Freeport-McMoRan and Vale were compared as a means to evaluate environmental calculation methodologies.

6.3. Freeport-McMoRan

Freeport reported on 3/15 Scope 3 categories as outlined by the Greenhouse Gas Protocol [94], but of specific interest are the Scope 3 categories relating to processing of sold products and use of sold products. When reporting 263 584 metric tonnes of CO₂e emitted for the Processing of Sold Products, the calculation methodology states that 'because Freeport-McMoRan operates vertically integrated assets, many downstream processing emissions that would be considered Scope 3 emissions for other companies are Scope 1 emissions for Freeport-McMoRan' [95, p 16]. This is reflective of Freeport-McMoRan owned smelters, where the emissions reported on processing of sold products 'only represent emissions from the smelting of concentrate and the refining of copper anodes sold to third parties' [95, p 16] and were calculated by applying average emissions at Freeport smelters to the amount of material sold to third parties. Freeport also reported that they 'do not have access to emissions information for the broad spectrum of downstream manufacturing' [95, p 16]

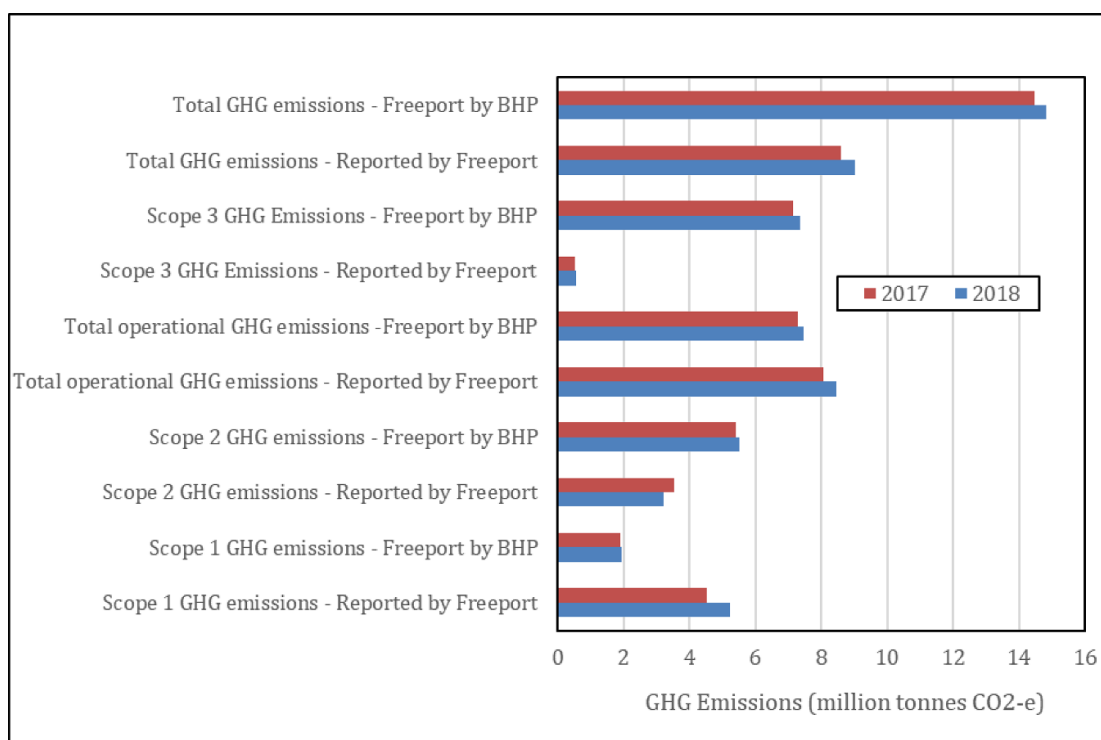


Figure 16. Freeport's 2018 reported emissions (copper, gold, molybdenum) vs Freeport's 2018 emissions using BHP methodology.

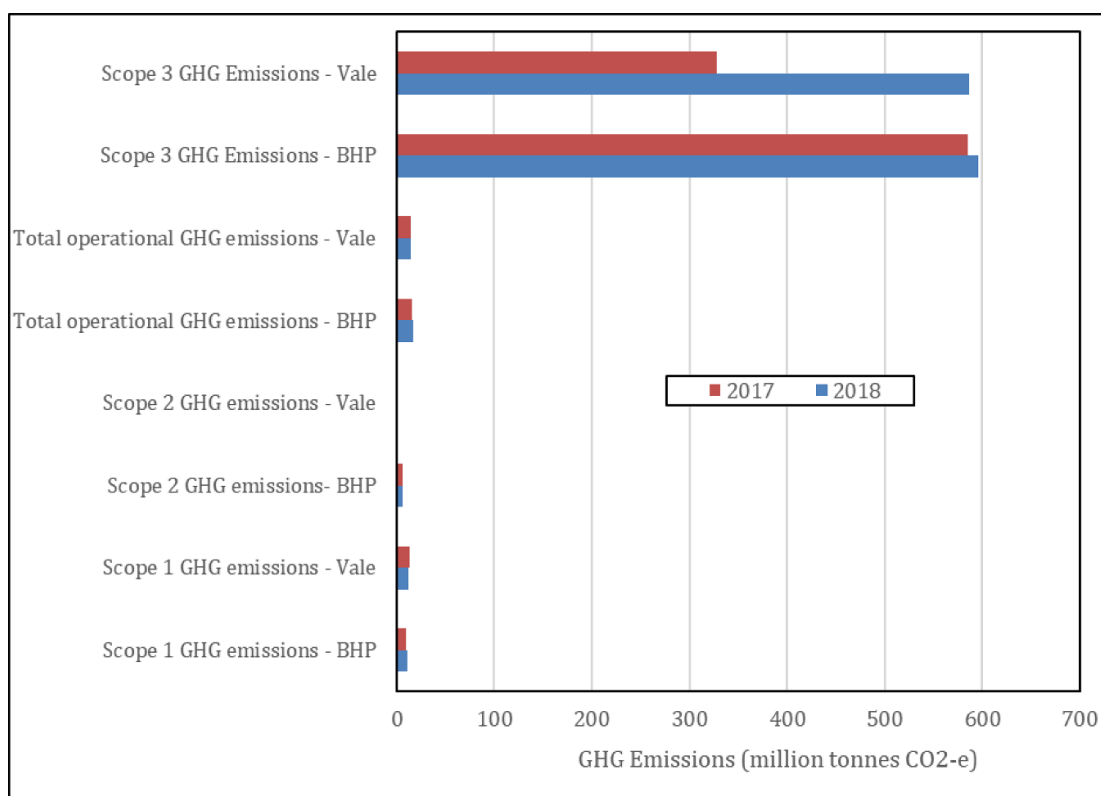


Figure 17. Reported emissions BHP vs Vale.

and chose not to report emissions for Use of Sold Products.

This study could not find material specific emissions for 2018, so for comparative purposes,

Freeport's 2018 copper production of 3813 million pounds, and sales of 3811 million pounds, were multiplied by BHP's calculated Scope 1 and 2 emissions factors and BHP's calculated Scope 3

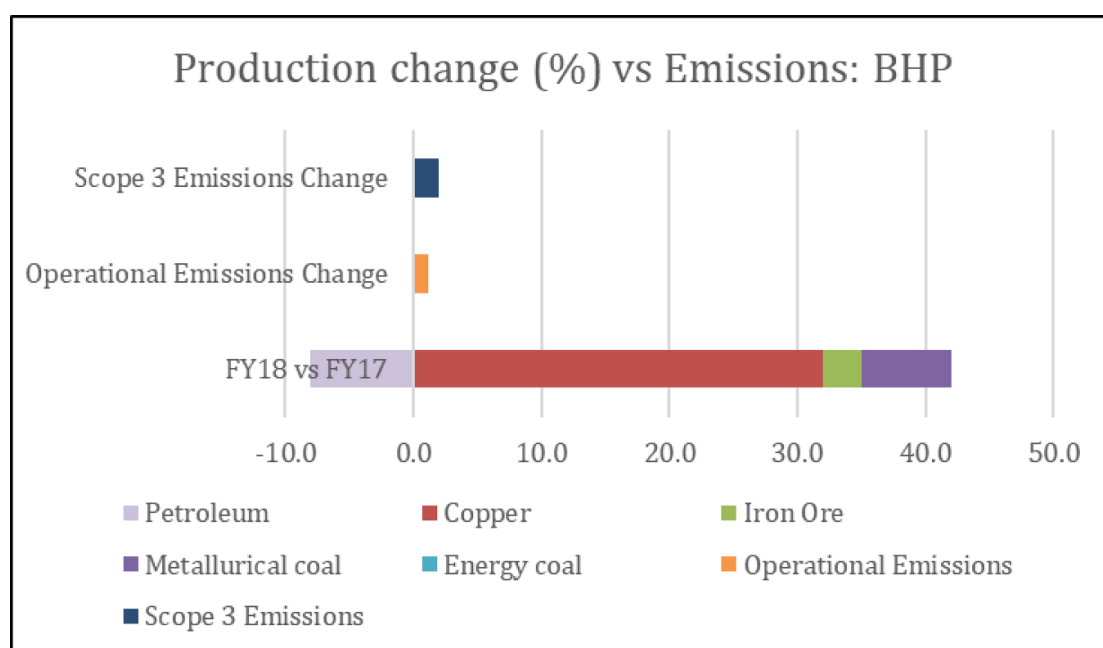


Figure 18. Production change vs emissions for BHP.

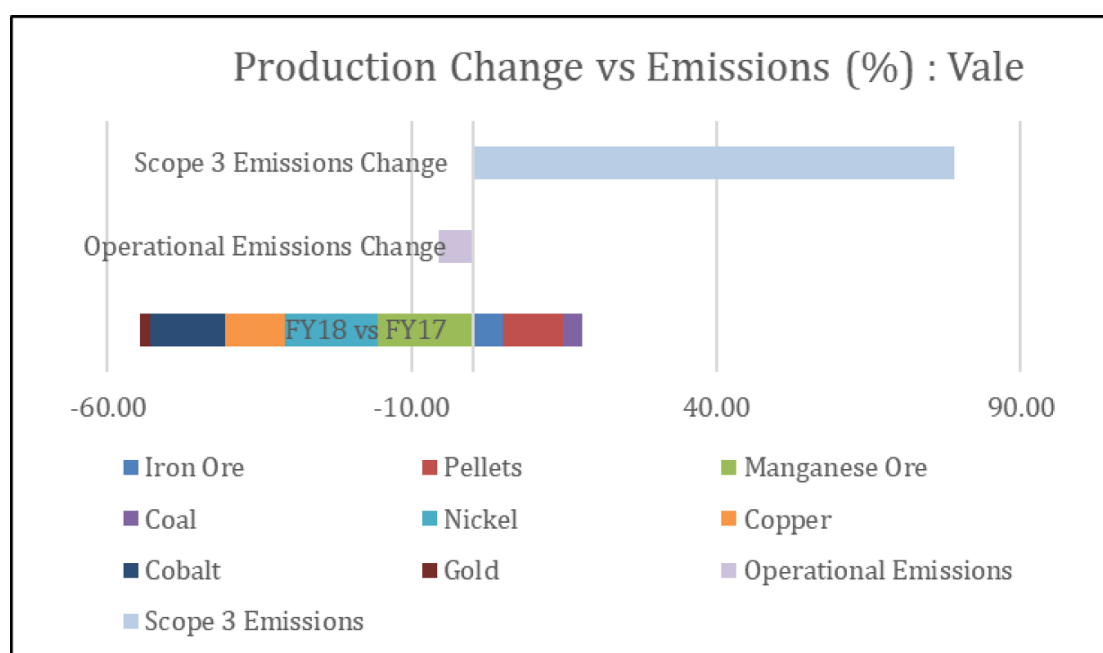


Figure 19. Production change vs emissions for Vale.

emissions factors (respectively) to get an estimate of Freeports emissions using BHP's methodology. These values therefore represent a conservative estimate of what Freeport would emit using BHP's methodology. Figure 16 shows how even ignoring potential emissions from Freeports production of gold and molybdenum, BHP's methodology predicts much larger emissions for Scope 3 emissions. Scope 1 emissions and total operational emissions are slightly lower using BHP's methodology, which is reflective of Freeport's vertical

integration, but overall, total reported emissions would be 64% higher for Freeport using BHP's methods.

6.4. Vale

Vale's emissions were relatively similar to BHP's, but its calculation methodology/strategy does not reflect its changes in operations and is indicative of drastic swings in reporting or problems with emission accounting. Vale does not take a vertical integration approach like Freeport, and its relative Scope

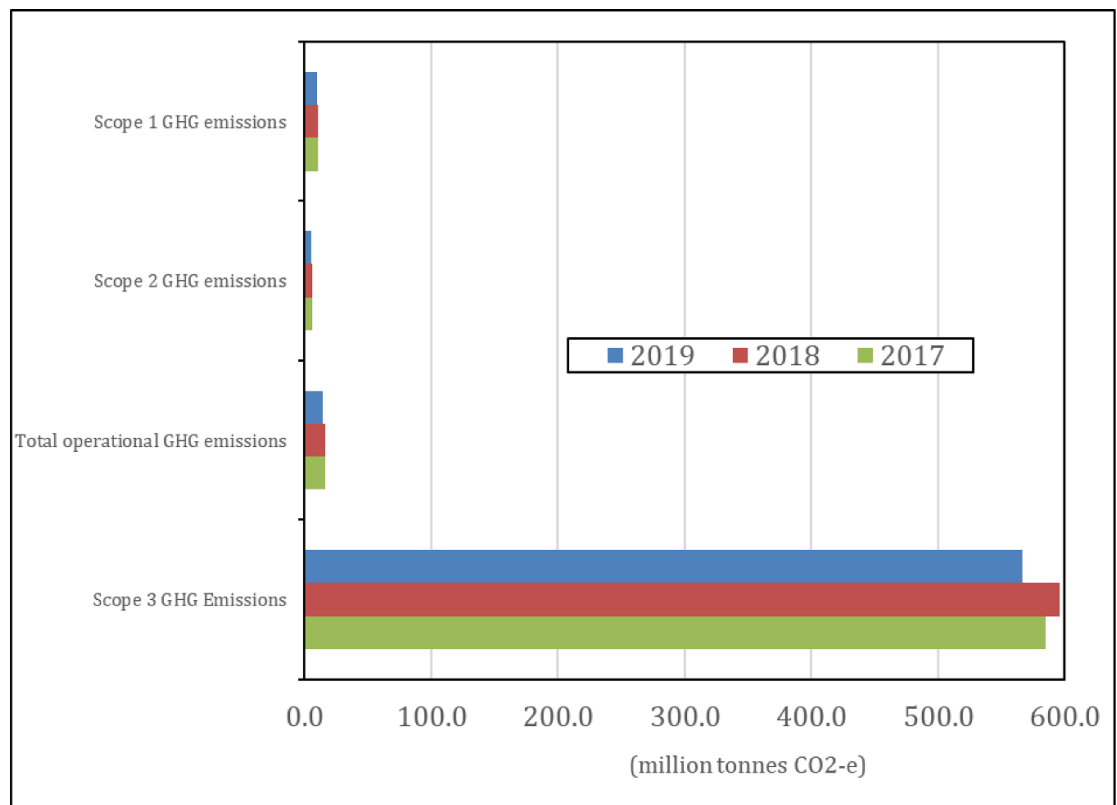


Figure 20. BHP operational emissions vs Scope 3 emissions.

3 emissions are similar to BHP based on reported emission values (figure 17), but its Scope 3 emissions drastically changed between 2017 and 2018. With a jump from 327.6 million tonnes of CO₂e to 586.2 million tonnes of CO₂e, Vale reported an almost 80% increase in Scope 3 emissions from one year to the next [90, 96].

A supplement could not be found to explain its reporting methodology, but Vale actively cites the Greenhouse Gas Protocol in both its 2017 and 2018 CDP report. In its independently published 2018 sustainability report, for Scope 3 emissions Vale wrote 'In 2018, these emissions totaled approximately 586 million tCO₂e in the year, a result very similar to that of 2017' [90, p 78]. The nearly 80% increase is not mentioned or explained. Operational changes also do not explain the shift, as Vale produced less manganese ore, nickel, copper, cobalt, and gold than in 2017. Small increases in iron ore, iron pellets, and coal, could not have caused such a drastic shift, unless the embodied emissions were over 13 000 tonnes of CO₂e per tonne of iron and over 27 000 tonnes of CO₂e per tonne of coal (assuming the same emissions as calculated from BHP, table 2). The cumulative production change relative to the change in Scope 3 emissions is shown in figures 18 and 19, with BHP's relative production and emissions changes shown for contrast. From this drastic shift, it can be assumed that emissions methodologies are still evolving despite the numerous forms of guidance,

and Vale's commitment to substantial Scope 3 values.

6.5. BHP

BHP has become a leader in disclosure transparency through its Scope 3 Emissions Calculation Methodology and unrestricted Scope 3 values (figure 20), but that does not mean it is without methodology concerns. For 2018, its Scope 3 emissions methodology relies on numerous assumptions and 'double counting' [92, p 4]. For its processing of sold products calculations, the Scope 3 Emissions Calculation Methodology 2018 used copper production of 1237 648 tonnes, citing the BHP Operational Review for the year end 30 June 2018 as the source, and with the assumption that 'production volumes approximate sales volumes; small year-end inventory volumes will be smoothed out over year-on-year calculations' [92, p 27]. However, BHP's Operational Review for the year end 30 June 2018 (published on 18 July 2018), reports 1753 kt of copper production for FY18, leaving nearly 500 000 tonnes of copper unaccounted for in its Scope 3 calculation, or over 2 million tonnes of CO₂e [92, 97]. This review was not able to reconcile these values. Without a mapped supply chain, the methodology also assumed a 1.0 conversion factor between copper feedstock and end-use product, along with assuming that all copper is manufactured into copper wire [92]. This is not an inherently flawed assumption, but it illustrates how generalized even

the most advanced calculation methodologies remain for GHG accounting along supply chains. Finally, the emissions factor used in the calculation is 4.2 tonnes CO₂e per tonne copper wire produced, which is based on a 2012 LCA that is meant to represent ‘all emissions associated with mining and extracting ore to create copper cathodes, as well as subsequent manufacturing into copper wires’ [92, p 28]. This emissions factor is presented as a ‘conservative’ assumption that is also meant to reasonably reflect ‘local electricity emissions intensity and other factors’ with no explanation how, or why, other than reminders that it will ‘provide a high-side estimation of emissions in BHP’s value chain from this process’ [92, p 28]. Together these values represent a calculated 8.57 tonnes of CO₂e per ton of copper produced by BHP, which is in contrast to the International Copper Association’s most recent LCA for cradle-to-gate copper, that cites the entire embodied emissions for 1 metric ton of copper cathode as 4100 kg CO₂e.

7. Conclusion and further research

Many committed governments, investors, companies, and consumers are searching for better ways to effectively identify and manage the environmental impacts of rapidly growing mineral supply chains. With the advent of a global economy, it has become difficult to track the impacts of the numerous inputs, processes, and activities involved with the use and production of minerals and metals. This lack of transparency has in turn highlighted the need for better methods and understanding of environmental impacts especially at the early stages of extraction and processing.

Our copper case study demonstrates that the mining industry’s ability to measure GHG emissions are likely inaccurate, incomplete, and differ dramatically from company to company. When looking at this variability for the same measurements, and for the same materials, it becomes clear that the process lacks cohesion and transparency. Even among what one would consider essential information, or highly quantitative values, such as CO₂e, the variance in methodology, inclusion criteria, and what is considered relevant, make it almost impossible to compare or evaluate a company’s effectiveness at reporting. BHP explicitly stated that they were overestimating their emissions to present themselves as taking a conservative approach. Other companies were able to select what emissions they chose to report or explain, and some left potentially enormous amounts of emissions unaccounted for. When considering these inaccuracies in the context of other minerals, metals, and mining companies, it is hard to claim that we have a clear understanding of the mining industry’s GHG emissions and environmental impacts. When further buttressed by the assumptions made through LCAs, and the lack of accounting for ASM, it is clear that the

environmental impacts of mineral and metal extraction are likely much larger than currently estimated. This has extremely troubling and sobering implications for those seeking to verify and validate the feasibility of a low-carbon transition.

In general, many of the world’s largest mining companies have tried to demonstrate their commitment to reducing their environmental impacts, but without consistency, it is difficult to create trusted data. A standardized method for reporting environmental impacts is needed. This review contributes towards this goal by identifying gaps in current reporting mechanisms, as well as best practices, and key potential areas for further analysis. In identifying these contours, environmental reporting by mining companies can be improved to better represent the evolving shift towards accountability that is needed for a low-carbon environment.

This review offers a benchmark for future corporate governance and understanding of metal and mineral supply chains. By starting at the beginning of the supply chain and focusing on extraction and processing, it is possible to identify several areas for further research and a comprehensive path forward. These actionable steps, and further work needed to implement them, are as follows:

- (a) The development of a more uniform, widely accepted and consistent carbon accounting framework for the metals and minerals industry.
 1. There needs to be alignment between companies on mineral-related standards and initiatives for accurate climate reporting. Discrepancies between inclusions, boundary definitions, and what type of data is considered viable, all make it impossible to compare carbon emissions across companies.
 2. A region-, or supplier-, specific open source database of carbon intensity factors for various products, process, and activities would allow for upstream users of these minerals to estimate supply chain emissions more reliably and accurately and could support sustainable procurement efforts.
- (b) Integration and sourcing of information from previous measurement efforts of energy security and material development. These sources will prove valuable in both political and technical approaches as lessons on mineral development can be applied to developing industries.
3. Continued monitoring of governance metrics (through initiatives such as the Resource Governance Index) and open dialogue with

developing nation will be essential in properly supporting countries involved in the energy transition.

4. More LCAs need to be used to raise awareness of governance shortcomings and environmental sustainability. Social LCAs can help companies understand how to maximize societal benefits from mining projects and raise awareness of potential pitfalls and lessons from other resource-rich nations. LCAs can also be used to help identify points of intervention within supply chains. The current top-down approach of having companies choose what to report is not conducive of mineral or environmental sustainability.
 5. If more reliable data becomes available, a meta-analysis of existing environmental issues would be essential to progress environmental accountability within the mining industry.
- (c) Transparency within supply chains and the implications of legislative actions need to be better considered when developing policy that affects the wellbeing of those in other nations.
6. Dialogues are needed for establishing cooperation between mining companies and government agencies in charge of plans for governance and communal development. In most countries, these dialogues are not well-established, and must be linked to wider efforts of diversification and growth.
 7. A method for mining companies to relay their positive environmental developments and be recognized for their continued efforts. The initiatives outlined in ESG reports are relatively superficial as companies are limited in their ability to accurately convey information. When actual progress can be conveyed, larger developmental change can be justified for the benefit of both the company and communities.

These points underscore how accounting for carbon and environmental performance across mineral supply chains is a complex, polycentric endeavor. It involves accounting frameworks and corporate governance institutions, transnational mining firms, ASM groups, intergovernmental institutions, suppliers, policymakers, and of course consumers. But this complexity of mining supply chains is not only a curse; it can also be a blessing, given that any one of these stakeholder groups can exert influence and pressure across the entire sector. And if there is a concerted push across many stakeholder groups, a coalition of those willing to be sustainable and promote

best practices, then mining may very well contribute towards our low-carbon and environmentally sustainable future, rather than risking to diminish it.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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